Lithium Battery and Ultra-Capacitor Aging

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Brian M Walker, Undergraduate Fellow MAE, UCD

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A National Center for Sustainable Transportation Research Report

September 2018

Brian M. Walker, Department of Mechanical and Aerospace Engineering, University of California, Davis

Mentors:

Kevin Mallon, Department of Mechanical and Aerospace Engineering, University of California, Davis

Professor Francis Assadian, Department of Mechanical and Aerospace Engineering, University of California, Davis

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Terms

1C- Charging/discharging at 1X capacity of battery
θ_c^{ref}- Reference temperature, capacitor
θ_c- Temperature, capacitor
θ_0- Initial temperature, capacitor
$C_{initial}$- Initial capacitance
C_{out}- Output Capacitance
I_{batt}- Current for battery
I_{cap}- Current for ultra-capacitor
K – Constant when voltage of capacitor is low, for aging
Pc, Pcap- Power to/from ultra-capacitor
Pbatt, Pb- Power to/from battery
PV- Photovoltaic
RC- Resistor/capacitor circuit
R_s- Series resistance
SOA- State of aging
SOC- State of charge
SOCb- State of charge of battery
SOCc- State of charge of ultra-capacitor
SOH_C- State of health capacitor
SOH_R- State of health resistor
T_{life}^{ref}- Life of capacitor, reference
UC- Ultra-capacitor
V- Voltage
V_0- Initial Voltage
V^{ref}- reference voltage
V_{batt}- Voltage of battery
V_{ocv}, V_{oc}- Open circuit voltage
V_T- Terminal voltage

Abstract

Electric drivetrains provide a solution to the rising emissions created by travel via vehicle transportation. Public transportation requires larger vehicles, buses and trucks for example, to have the ability to carry large loads such as many passengers or cargo. These larger vehicles have a low fuel economy and higher emissions output than conventional vehicles because of larger average load conditions. Supplementing internal combustion engines with electric power will lower emissions created by these vehicles directly. Electric power efficiency, along with internal combustion engine efficiency, lower over time because of battery aging or internal wear and tear (combustion engine). Battery aging is an important variable to keep in mind when electric power is introduced because batteries have a limited cycle range which in turn limits their amount of usage before replacement is needed. By adding ultra-capacitors to take power load away from the battery, battery aging will be diminished.

Introduction

Lithium based batteries serve as the current main battery of choice for vehicle transportation because of their high energy density and ability for high cycle life. Improving cycle life of lithium batteries means limiting large currents in and out of the battery as much as possible to lower degradation and heat affects. Solar photovoltaic cells (PV) and ultra-capacitors (UC) can be added to vehicles to improve battery life by adding energy either through PV cells, sun radiation, or regenerative braking by taking excess power away from the battery and storing it in temporary energy storage. Capacitors can quickly unload power back into the system for high load situations such as a hard acceleration, taking away the need for a high-power drain from the battery.

In general, PV cells were only used to get accustomed to Simulink and modeling. No tests on aging were completed using PV cells. Also, PV cells supplement charge only to reduce aging by reducing the depth of discharge. PV cells affect aging of the battery very differently than UC's.

MATLAB is a powerful tool and gives the user an abundant ability to compile extensive calculations very fast. Simulink is program linked within MATLAB that is used for modeling and simulating complex environments that can be static or dynamic. Simulations allow for non-destructive testing so expensive battery systems are not worn out or needed for results. The simulations done in this research are dynamic simulations over time. Individual models of vehicle dynamics, battery systems, capacitors and power management are put together to model and simulate a bus with set physical, battery and capacitor parameters to understand how a battery degrades over time. Through these simulations capacitors are added to the system to compare the life cycle of the battery.

Multiple models were used to put together the final simulation. From [1], a vehicle dynamics model of a basic electric bus was built and simulated with and without the addition of PV cells on the roof to compare battery state of charge (SOC) over time. Next, multiple order UC systems were modeled using the model description in [2]. Finally, the vehicle dynamics model, minus the PV cells, was put together with the 4th order UC model along with an energy management system limiting power either positive, regenerative braking, or negative, power requested preventing the battery or UC from getting too much power either way.

Aging models were then added to both the battery and UC. The high temperature low voltage aging model was used from [3] to provide the state of health (SOH) of the UC system. Battery aging considers the effects of temperature, capacity fade and resistance growth. The model used for battery aging was based off of experimental data in [4].

Ultimately, by adding a UC to a battery system, the battery was alleviated of high loads when power is requested or given back to the battery during regenerative braking, lead to more cycles the battery can complete during its lifetime.

Simulation Models

Vehicle Dynamics

A vehicle dynamics model was first created to mimic the properties of a bus used for public transportation using an all-electric battery and drivetrain. The model is derived from a bus model created by [1] that lays out the bus dimensions, battery parameters and PV parameters. Equations 1-13 were used from to develop the model and Tables 1-2 were used from [1] to set parameters.

Simplified Equations:

$$F_{traction} = F_{drag} + F_{roll} + F_{inertial} + F_{gravity} \tag{1}$$

Equations 1 are derived from force equations of gravity, inertia, drag and rolling resistance on the bus.

The bus was then run on a pre-determined Orange County and Manhattan bus drive cycles with given outputs of acceleration and velocity over the duration of the cycle. See Figure 1 for a velocity profile of the drive cycle.

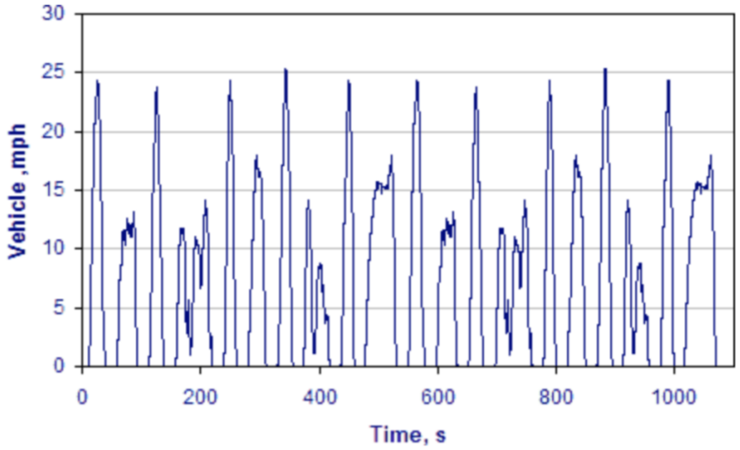

Figure 1: Manhattan County Drive Cycle

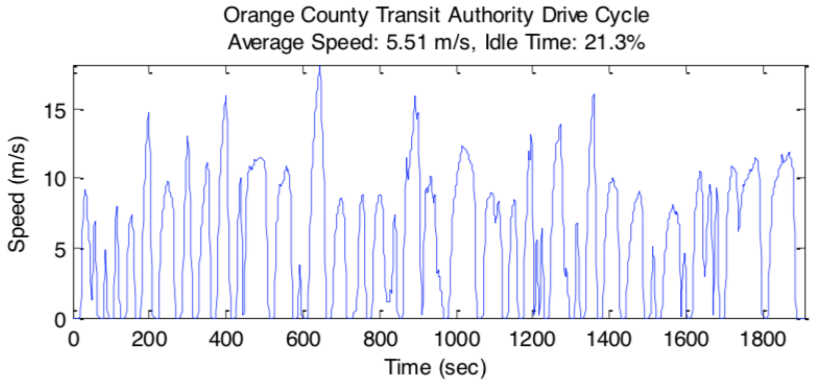

Figure 2: Orange County Drive Cycle

Battery Model

The first battery model was also modeled after [1] using Table 3 and equations 14-25 within the resource. Equations 2 and 3 are simple Ohm's law equations that are put together to form a quadratic equation. The quadratic equation is solved in equation 4 to find the terminal voltage of the battery. From there power required by the battery (Pbatt) can be found.

Simplified equations:

$$V_T = V_{ocv} - I_{batt} * R_{eq}\ ,\ I_{batt} = P_{batt}/V_T \tag{2-3}$$

$$V_T = \tfrac{1}{2}(V_{ocv} \pm \sqrt{V_{ocv}^2 - 4 * P_{batt} * R_{eq}}) \tag{4}$$

Power required by the vehicle is then converted to current using the number of battery cells in parallel and series to get the current for one cell. This model was only used with PV cells.

The final battery model was more complex and was modeled after [4]. A circuit representation of the model is shown in Figure 3.

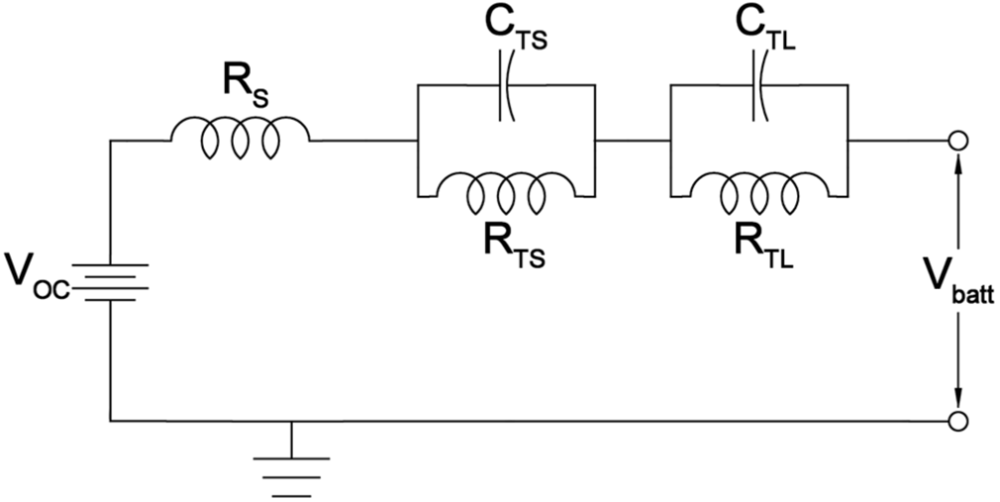

Figure 3: Circuit Representation of Battery Simple Model

The battery model from [1] was then updated to a 2nd-order model as given in reference [4]. A circuit representation of the model is shown in Figure 3. Equations 2 and 8-12 from reference [4] were used to model the internal resistances and capacitances as a functions of battery state-of-charge (SOCb).

Simplified equations:

$$V_{ocv}(SOC) = -1.031exp(-35SOC) + 3.685 + 0.2156SOC - 0.1178SOC^2 + 0.321SOC^3 \tag{5}$$

$$R_{series}(SOC) = 0.1562exp(-24.37SOC) + 0.07446 \tag{6}$$

$$R_{Transient_s}(SOC) = 0.3208exp(-29.14SOC) + 0.04669 \tag{7}$$

$$C_{Transient_s}(SOC) = 752.9exp(-13.51SOC) + 703.6 \tag{8}$$

$$R_{Transient_L}(SOC) = 6.603exp(-155.2SOC) + 0.04984 \tag{9}$$

$$C_{Transient_L}(SOC) = -6056exp(-27.12SOC) + 4475 \tag{10}$$

Equations 5-10 shown above were integrated into the original battery model as a function through MATLAB within Simulink. The output was dynamic results to resistance, capacitance and open circuit voltage of the battery as a function of SOCb. The battery model uses a 2nd order RC circuit representation to gather more realistic results of battery activity due to hysteresis. Hysteresis effect is due to delays in chemical reactions internal to the battery during charging and discharging. This effect can be seen in a test on the battery model in Figure 4.

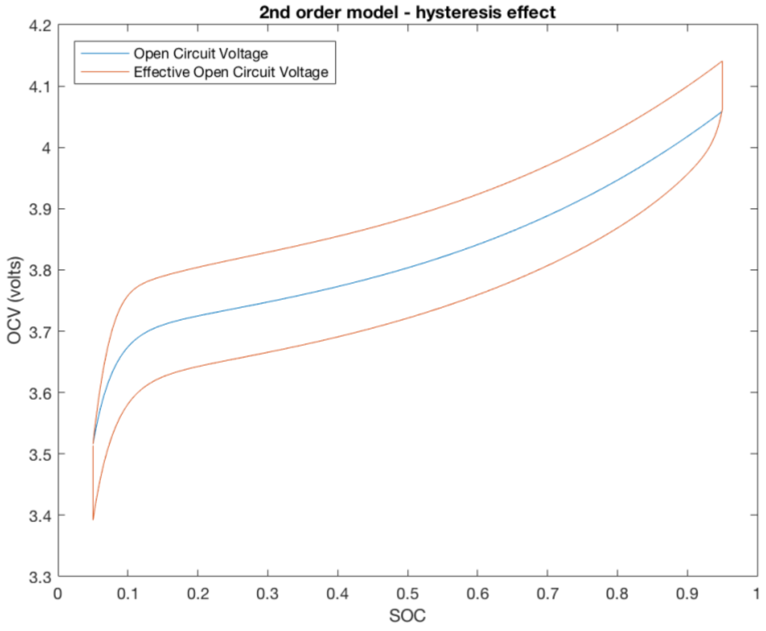

Figure 4: Hysteresis Effect on Battery Charging, Discharging

A simplified model of the aging model integrated with the battery model is shown in Figure 5.

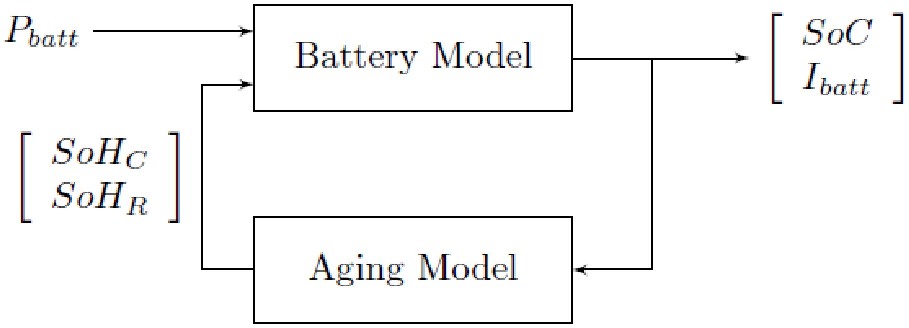
P_{batt}
Battery Model
$\begin{bmatrix} SoC \\ I_{batt} \end{bmatrix}$
$\begin{bmatrix} SoH_C \\ SoH_R \end{bmatrix}$
Aging Model

Figure 5: Aging Integrated into Battery Model

Power for the battery (Pbatt) goes into the battery model as well as SOHc and SOHr, the state of health of the capacitance and resistance respectively using a model based from [6].

Capacitor Model

The ultra-capacitor model was simplified at first to look at the differences between ordered systems. 1st through 4th order RC circuits were built in Simulink using resource [2] for model and parameters of resistors and capacitors. Figure 6 shows the circuit representation of each order system. 1st order would just be more simplified version of the 2nd order system, for example, as it is not shown in Figure 6.

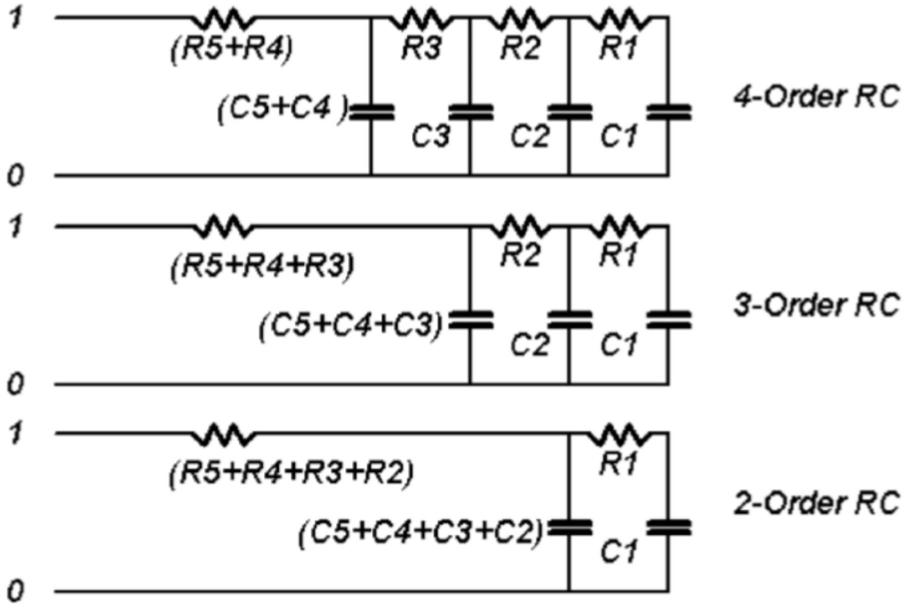

Figure 6: RC Circuits, Different Order Systems [2]

Expected output was that 4th order systems would show a more accurate result. Modeling a 4th order circuit allows more paths for current to flow at different rates. Time constants are different as resistance and capacitance for each leg are different leading to the need to model the more complex, less simplified model. Figure 7 show results of passing 1 watt of power through each order RC circuit.

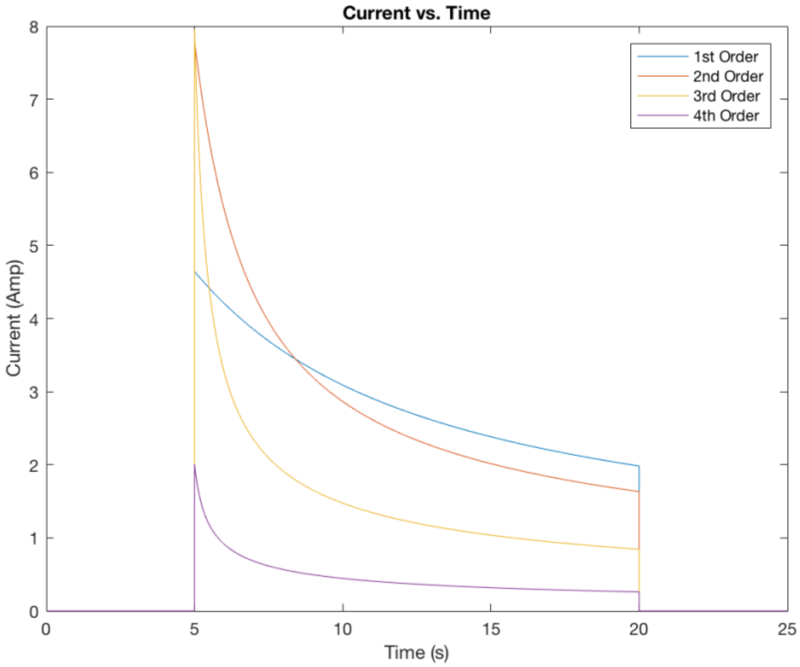

Figure 7: Different Order Capacitors Current, 1 watt for 15 seconds results

The 4th order model was chosen and modeled in Simulink even though the more complex system might add time to computational calculations. In the end, modeling a higher fidelity RC circuit did not change computational time enough to deter more accurate results.

Capacitance aging was then added to the UC system. From resource [3], a high temperature low voltage aging model was used. Equation 3 and Table 2 were used from 3 to develop the model.

Simplified equations:

$$\frac{dSOA}{dt} = \frac{1}{T_{life}^{ref}} * exp(ln(2)\frac{\theta_c - \theta_c^{ref}}{\theta_o}) * [exp(ln(2)\frac{V - V^{ref}}{V_o}) + K] \tag{11}$$

For each capacitor C_i or resistance R_i shown in Figure 6, $C_{i,intitial}$ and $R_{i,initial}$ denote the unaged capacitance or resistance.

$$C_{out}(SOA) = C_{initial}(0.95 - 0.15SOA) \tag{12}$$

$$R_i = R_{i,initial}/(1 - 0.3SOA) \tag{13}$$

Equation 11 shows State of aging, SOA, of the UC as a function of expected life, temperature, voltage and a constant K. K is dimensionless and replaces the voltage term whenever voltage is low. Figure 8 shows the simplified model of the UC integrated with aging.

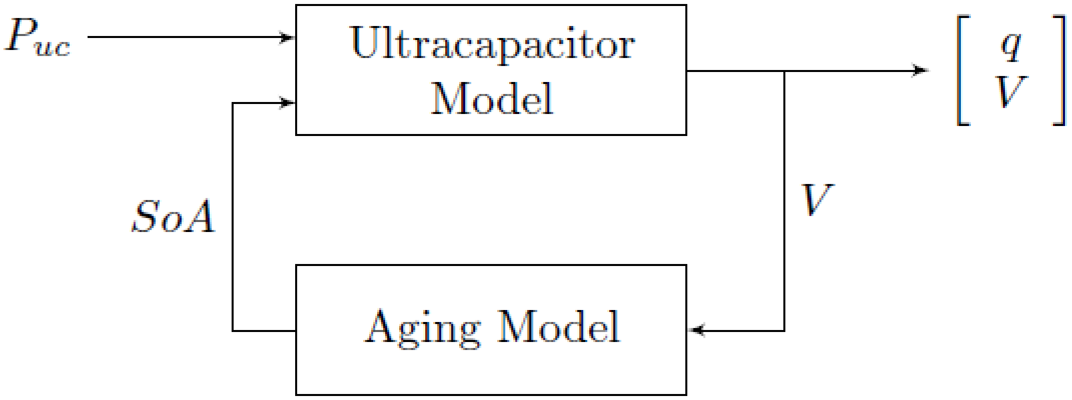

Figure 8: Aging integrated into UC

Integrating previous models of vehicle dynamics and the 4th order UC along with aging models from [3] and [4], a complete vehicle simulation can be run. Each UC, called a UC cell, include 100 individual UC's in series along with 100 in parallel.

Energy Management Model

The energy management model is a MATLAB function built into Simulink the controls the amount of power going to and from the UC and the battery. Inputs include the power required by the bus (Preq) the state of charge of the battery (SOCb) and the state of charge of the UC (SOCc). Outputs include power to and from the battery and the UC. Figure 9 shows a simplified model of the energy management system.

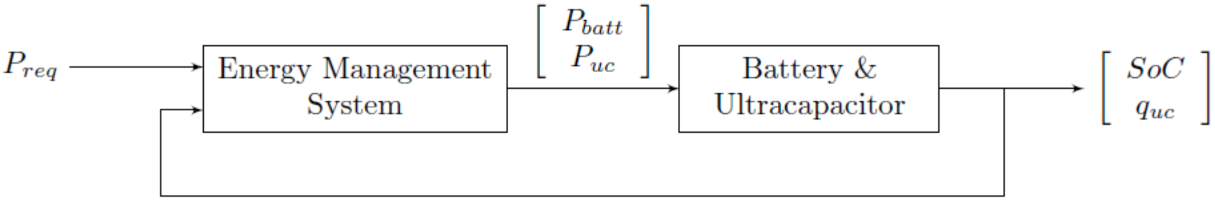
P_{req}
Energy Management System
$\begin{bmatrix} P_{batt} \\ P_{uc} \end{bmatrix}$
Battery & Ultracapacitor
$\begin{bmatrix} SoC \\ q_{uc} \end{bmatrix}$

Figure 9: Energy Management System Model

The energy management system uses a peak shaving method, shown in Figure 10, to cap power to and from the battery making sure the absolute max, acceleration, and absolute minimum, regenerative braking, are reached but not exceeded within the battery. Battery state of charge is maintained between 20-90% at a charging rate of 1C to minimize aging effects. The UC is designed to be able to either take or absorb the rest of the electrical power needed throughout the cycle the battery cannot handle. This alleviates any issues with excess energy and nowhere to store it. UC state of charge is maintained between 20% and around 50% to maintain a low voltage for minimal aging.

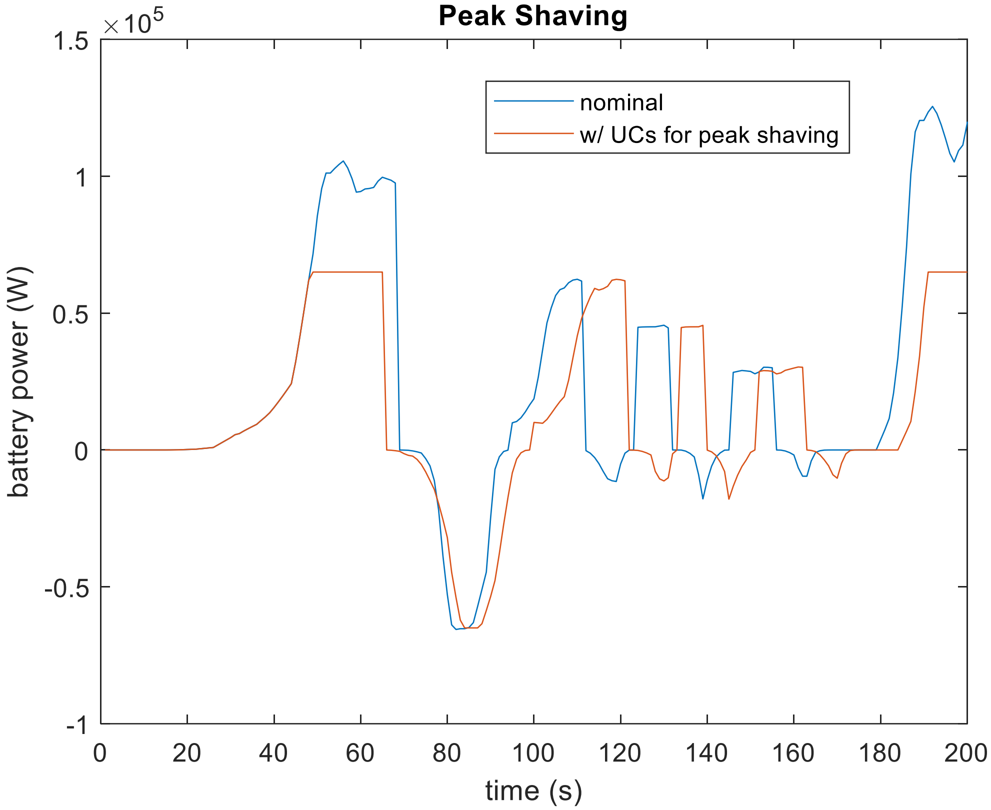

Figure 10: Peak Shaving- battery is constrained to a low minimum and maximum power

Integrated Dynamic Model

Integrating the vehicle dynamics model, adding in motor and transmission efficiencies, both battery and UC models with aging to the energy management model, the final model for testing takes shape. The Manhattan drive cycle is used in the final tests. Figure 11 shows the overall look of the integrated model.

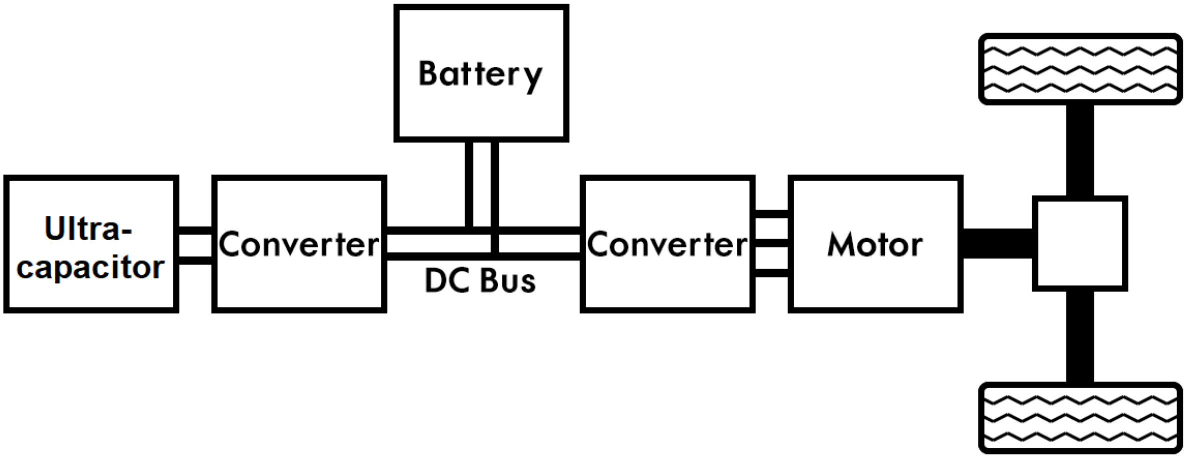

Figure 11: Integrated Dynamic Model

Simulation Results

First, the vehicle dynamics model was run with a battery that did not age using the first battery model from [1]. The simplified model was put together with the Orange County drive cycle along with and without PV cells to see how the battery life changed.

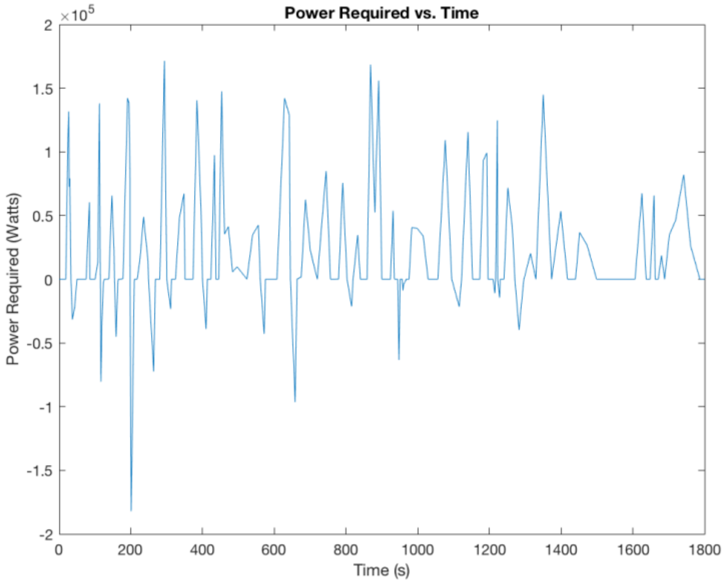

Figure 12: Power Required for Bus to Drive on OC Drive Cycle

Comparing Figure 12 to Figure 13, the jagged edges of SOCb show that when a spike of electrical power is required, the battery is drained. Figure 13 also shows the difference in SOCb for when the PV is added to the system giving an overall larger SOC leading to longer battery life and run times.

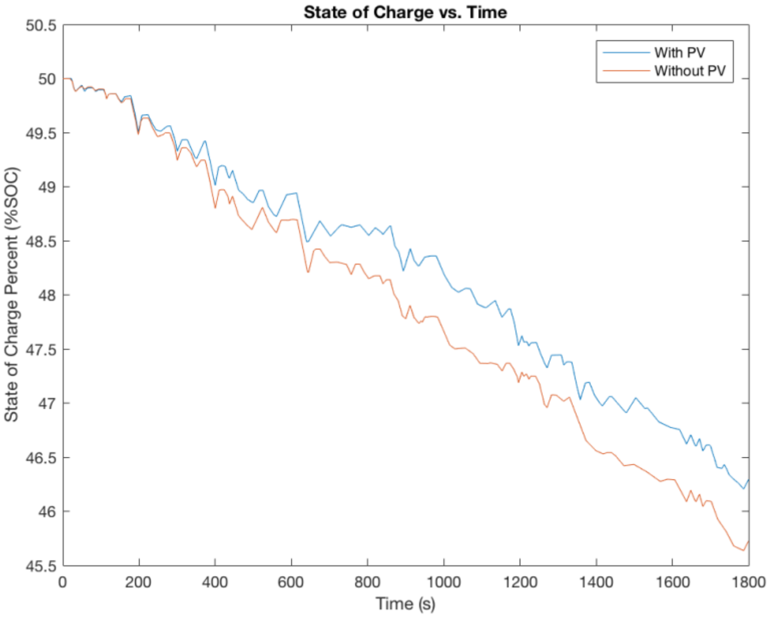

Figure 13: SOC of onboard battery with and without photovoltaic cells

The takeaway was that adding a supplemental power source such as a PV adds to the battery life allowing for the ability to drive longer on a single charge.

Next, the PV cells were taken away and the Integrated Dynamic Model from Figure 11 was used in entirety on the Manhattan cycle using the final battery model from [4]. Four tests were run. The first test included only the battery while aging. The second test included one UC cell that did not age. The third test only changed the UC cell to age instead of not aging. The fourth test was to include 3 more UC cells for a total of 4 that all aged. Battery cycle life results are shown in Table 1. One cycle life is equal to one full drive cycle. For example, four hours of driving on the Manhattan drive cycle is equal to one battery charge/discharge for this test data. Each test began with a new battery and was run until the battery reached its end-of-life condition (20% capacity fade).

Table 1: Cycle life of battery

Type of System	Cycle Life
Battery aging only	3839
Battery aging with 1 UC	4001
Battery aging with 1 aging UC	4000
Battery aging with 4 aging UC's	4069

Figure 14 and 15 show the battery cycles in a table graph showing the vast difference between not having UC's and having them part of the system. There is not much difference between having one UC and then having one UC while aging showing aging is not entirely significant when compared to the aging of the battery.

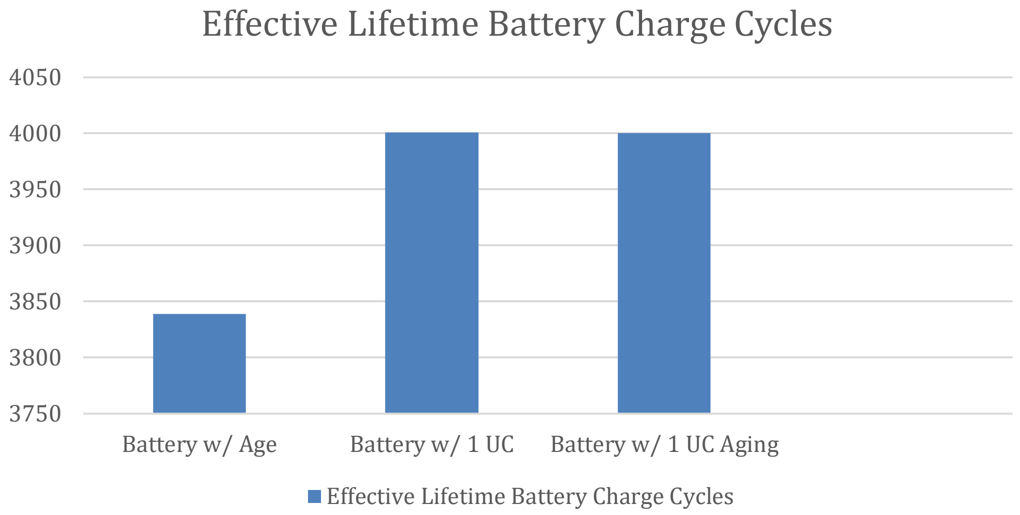

Figure 14: Effective charge cycles of battery with aging with different conditions

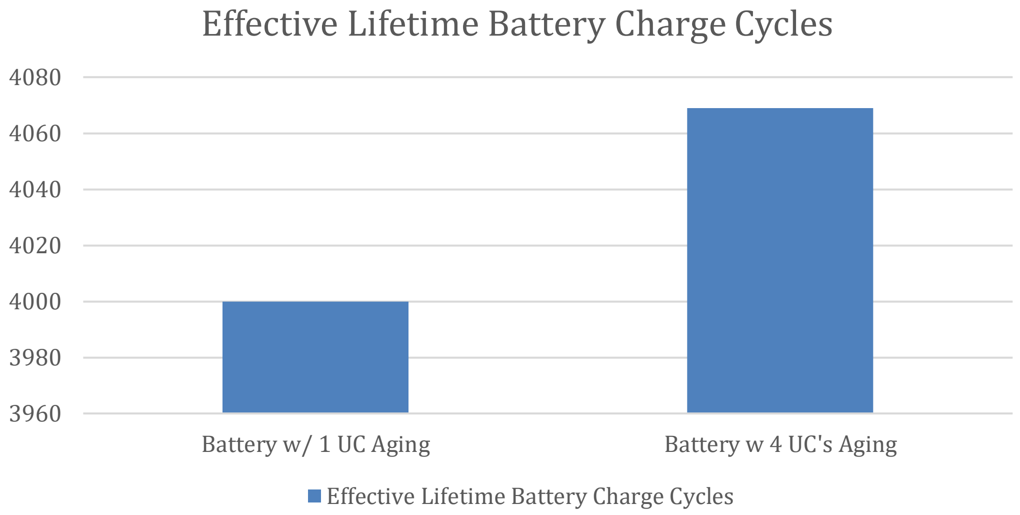

Figure 15: Effective charge cycles of battery with aging UC's

With the addition of more UC cells to the system, a significant increase in the amount of battery cycles occurs. This shows that by adding more UC's, the battery can become more efficient.

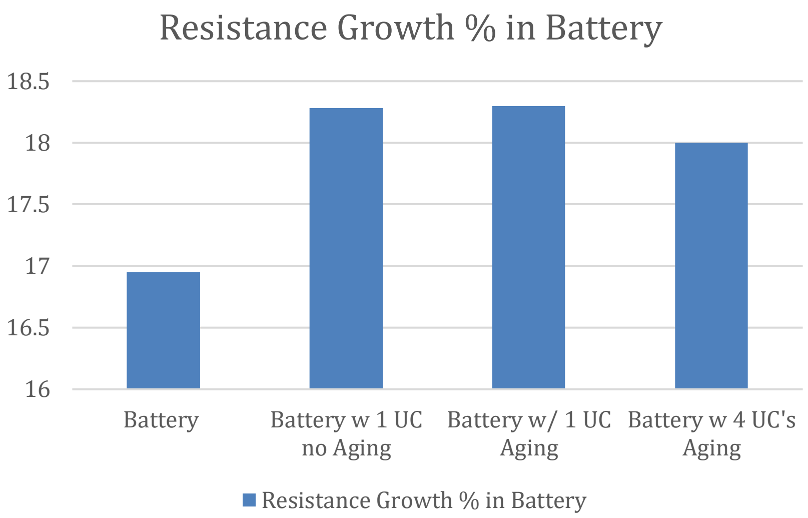

Figure 16: Resistance Growth in the Battery

Figure 16 shows resistance growth internal to the battery in response to aging. As UC's are added to the system the resistance growth decreases which allows the battery to not age as fast. The difference between the battery and the battery with UC leads to an investigation to why the battery alone has less resistance than the battery with help from a UC. All other results show the outcome assumed.

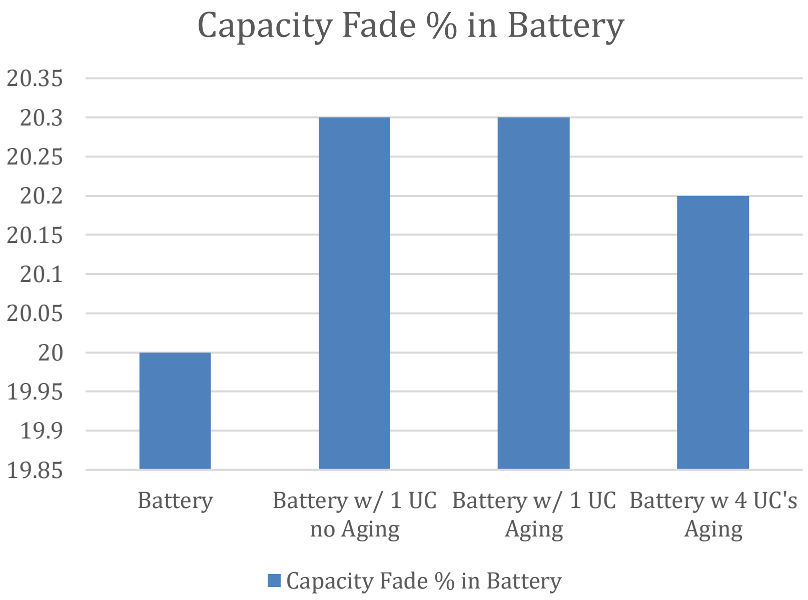

Figure 17: Capacity Fade of the Battery

Figure 17 shows capacity fade within. Each test was run until 20% capacity fade was reached, so Figure 17 confirms that the simulations ended at the correct time.

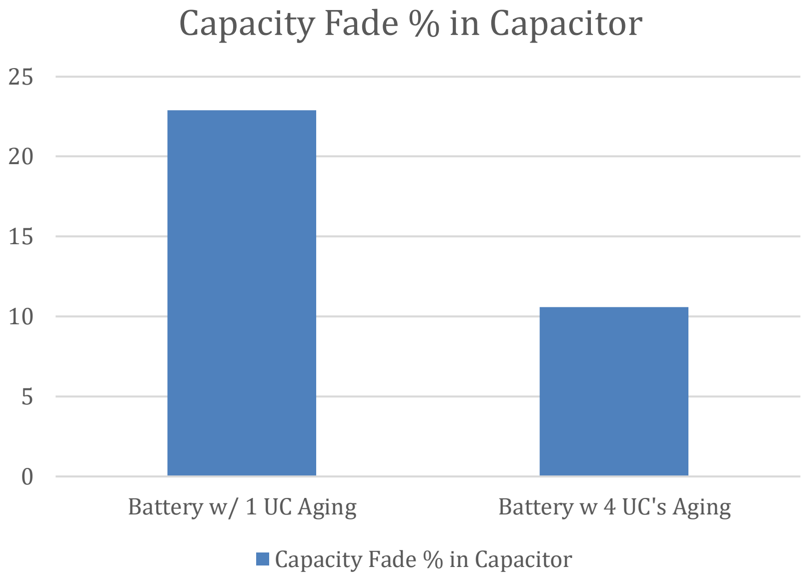

Figure 18: Capacity Fade in the UC

Aging within the UC cell, as seen in Figure 18, shows a trend where the more you UC's you add to the system, the less each UC ages. More UCs means that the individual UC cells can operate at a lower voltage, so this result was expected. However, it shows that there is a limit of how much additional UCs can reduce aging. A 300% increase in the number of ultracapacitors added only 69 new cycles to the battery (a 42% increase) and extended the UC lifetime by 120%. So, the newly added UCs did improve battery aging but not by as much as the original UCs. This result shows a need to do a cost analysis at a later date.

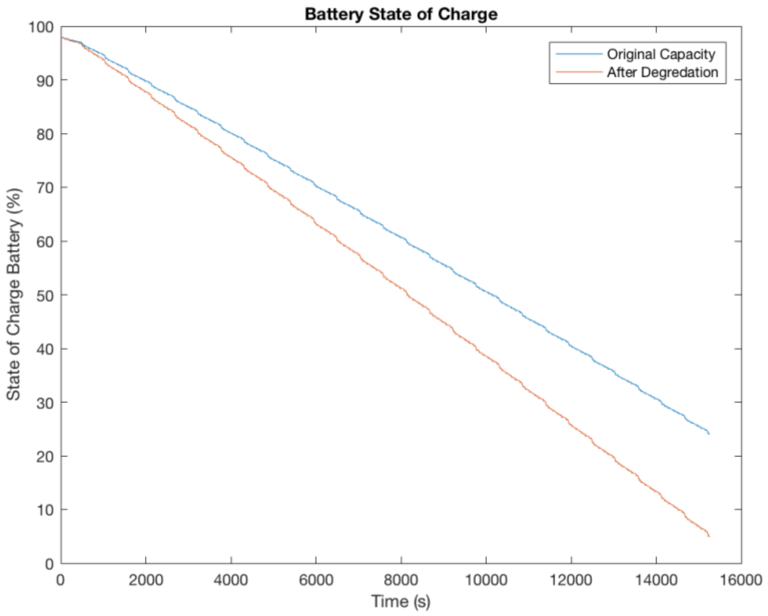

Figure 19: Battery SOC Before/After Aging

Figure 19 shows the difference between a battery at start-of-life (unaged) and at end-of-life (aged) through the same Manhattan drive cycle. With the difference being about 20% SOC, taking aging of the battery into account is an important step in developing a successful integrated dynamic model.

Discussion

Aging within the battery is a function of SOC and is caused by a buildup of internal resistance following a loss of capacity. Anode resistance is the main impact in overall resistance. Loss of active lithium throughout the chemical reaction process leads to aging as well [5]. Batteries are more thermally stable than capacitors. Aging within the UC is caused by high heat and high voltage. Thermal stress impacts UC's significantly [3]. Also, UC's do not age well initially dropping to 95% efficiency after using them once [3]. With that being said, these test results how that UC aging is insignificant when compared to battery aging.

While UC's can only handle quick bursts of electrical power, they can also unload them quickly. UC's minimize power fluctuations within the management system to alleviate the battery of high load conditions thus leading to less aging of the battery overall when used together. With the addition of more UC cells to the battery, cycle life increased, capacity fade decreased, and resistance growth decreased within the battery.

Resistance growth and capacity fade, in theory, should be larger when the battery runs as part of the system alone when compared to being paired with a UC. The data acquired did not show this so further investigation is needed to either confirm this action or realize an error in calculation. Also, a cost analysis should be done comparing the use of UC's to the integrated dynamic model to find the ratio where cost equals the amount of UC's as to not over spend on un needed energy storage. A higher fidelity model should also be built to replace the integrated dynamic model to then be compared to it to identify if a higher fidelity system should be used for future tests.

A test bench model should be built using a battery with and without a UC cell to test results found in this paper and compared to a higher fidelity system. A controller should be used for the test bench model to have the ability to re program using different methods of distributing power, replacing the peak shaving method to compare results.

Conclusion

Different models were integrated using MATLAB and Simulink to simulate battery life cycle and aging characteristics of both a battery and a UC cell. UC aging was found to be insignificant when compared to battery aging. By adding more UC cells to a battery system, the battery aging decreases followed by a large decrease in UC aging. By adding 4 UC cells to a battery, the

UC life increases about 2.2 times and battery life increases 1.4 times when compared to using just one UC.

More tests will be run to increase accuracy and to compare to aging results presented in this paper. Also, a test bench model would be integral to performing real world results and comparing them to results in this paper as well as a higher fidelity model.

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